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# Modification of the wind erosion roughness index by rainfall

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## Abstract

The cumulative shelter angle distribution (CSAD) is a soil surface roughness index used in the "wind erosion prediction system" to estimate the fraction of the soil surface susceptible to abrasion by saltating particles (*FSA*). However, little is known of the effect of rainfall amount and intensity on CSAD parameters. This study was conducted to determine how and to what degree simulated rainfall amount and intensity affect CSAD parameters and ridge height in a field with low (92 mm) ridges. Simulated rainfall was applied in cumulative amounts of 0, 6, 19, 32, 44, 57, and 83 mm at intensities of 13, 25, 51, and 76 mm h$^{-1}$ on duplicate plots of an Acuff sandy clay loam (fine-loamy, mixed, thermic Aridic Paleustoll). The CSAD parameters were estimated from elevations measured by a laser roughness meter in directions parallel and perpendicular to tillage after each cumulative rainfall amount. Laser roughness meter measurements were also used to calculate ridge height for each plot. We found the CSAD parameters varied in response to tillage direction. The mean *FSA* was 19% greater and the rate of change of *FSA* over rainfall amount was twice that when evaluated parallel to tillage compared with measurements made perpendicular to tillage. The CSAD was a more sensitive index than ridge height for describing the effects of rainfall and tillage on surface roughness. Analyses of variance of CSAD parameters and *FSA* revealed significant differences ($P < 0.05$) owing to rainfall amount and intensity for most parameters. No significant differences in ridge height ($P < 0.05$) were found to be due to rainfall amount and intensity. The 13 mm h$^{-1}$ rainfall intensity had no effect on the roughness parameters. Regressions of CSAD parameters and *FSA* over rainfall amount for each rainfall intensity showed that data for the 51 and 76 mm h$^{-1}$ rainfall intensities could be combined. This study clearly demonstrated the sensitivity of CSAD parameters to rainfall amount and intensity. The response of

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CSAD parameters to tillage direction confirmed and quantified the value of tillage as a wind erosion control practice. 

*Keywords:* Microrelief; Microtopography; Abrasion; Tillage; Ridges; Rainfall intensity

## 1. Introduction

Soil surface microrelief or roughness refers to small-scale differences in ground-surface height measured over relatively short distances. Roughness measurements are used in wind and water erosion prediction equations and have applications in hydrology, agroclimatology and other areas. For applications in erosion models, roughness is often measured over distances of about 1 m.

Measurements of soil surface roughness have been made for many years for various applications using a variety of instruments and mathematical descriptions of the soil surface (Hirschi et al., 1987; Zobeck and Onstad, 1987; Robichaud and Molnau, 1990). In agricultural soils, tillage often creates an oriented roughness with ridges running parallel to the tillage direction. In addition, the random orientation of clods or aggregates on the soil surface creates a random roughness. Some of the earliest roughness parameters described random roughness using the standard deviation of surface elevations or similar statistics (Kuipers, 1957; Allmaras et al., 1966; Currence and Lovely, 1970). More recently, Römkens and Wang (1986, 1987) have described oriented roughness based on peak frequency and calculated surface area per unit length. Comparisons of several proposed roughness parameters have been made by Currence and Lovely (1970) and Bertuzzi et al. (1990).

The ability of oriented roughness (ridges) to reduce wind-induced soil erosion (wind erosion) has been well-documented. Early studies have shown that 65 mm high ridges oriented perpendicular to the wind reduced erosion rates by up to one third the rate of smooth surfaces (Chepil and Milne, 1941). Later studies confirmed this result. Armbrust et al. (1964) found that 51 and 102 mm high ridges reduced the quantity of soil eroded by wind by 67% compared to a smooth surface. Fryrear (1984) measured a 85% reduction in eroded soil for 64 mm high ridges. Higher ridges afforded even greater protection. This effect of oriented ridge roughness is known as the soil ridge roughness factor in the wind erosion equation (Woodruff and Siddoway, 1965). The effect of random roughness was not addressed in the wind erosion equation.

The USDA, Agricultural Research Service (ARS) has developed a new computer-based wind erosion prediction system (WEPS) to make daily estimates of wind erosion (Hagen, 1990). WEPS requires daily estimates of soil surface roughness to make erosion predictions. Soil surface roughness is important in wind erosion prediction because it influences trapping and emission of soil particles, abrasion of the soil surface by saltating grains, and the development of wind profiles (Hagen, 1988).

The interaction of saltating soil particles and surface roughness is especially important in understanding the wind erosion process. During wind erosion, saltating particles are lifted from the soil surface and transported downwind where they impact the soil surface. The point of impact is influenced by the particle jump length, angle of descent and surface roughness (Potter et al., 1990). Surface roughness can act to shelter or protect part of the surface from the impact of saltating particles. Since none of the previously proposed roughness characterization methods were capable of describing the sheltering effect of surface roughness directly, Potter et al. (1990) developed a new wind erosion roughness index called the cumulative shelter angle distribution (CSAD). WEPS uses the CSAD to quantify soil surface roughness and to estimate the fraction of the soil surface susceptible to abrasion by saltating particles (*FSA*).

Potter and Zobeck (1990) described the CSAD as a two-parameter Weibull function:

$$SF = 1 - \mathrm{EXP}\left(-\left(\frac{SA}{B}\right)^{C}\right) \tag{1}$$

where *SF* is the surface fraction of observation points having a shelter angle less than or equal to a given shelter angle, *SA* is the given shelter angle, and the *B* and *C* parameters may be estimated by least-squares non-linear regression. The *B* parameter is a scale factor and the *C* parameter is a shape factor. The CSAD accounts for the effects of random and oriented roughness. Cumulative shelter angle distributions measured perpendicular to tillage include roughness owing to oriented tillage marks and random roughness caused by clods on the soil surface. It was assumed that the effects of ridging would be minimal in the direction parallel to tillage and CSAD would represent only non-oriented, random roughness (Potter and Zobeck, 1990). Potter et al. (1990) have shown that CSAD is sensitive to tillage direction, tillage tool, and rainfall. However, details of how these factors affect CSAD are not yet known. This study was performed to explore the sensitivity of CSAD parameters in describing the response of a ridged soil surface to rainfall of varying intensities. Specifically, we test the hypothesis that the effect of rainfall on CSAD parameters for a ridged field is influenced by rainfall intensity by evaluating four rainfall intensities to determine precisely how each intensity affects CSAD index parameters. In addition, we contrast the use of ridge height and the CSAD in describing soil surface roughness. This information will be useful for models that estimate wind erosion on agricultural fields after tillage and subsequent rainfall.

## 2. Materials and methods

### 2.1. Study site and experimental design

The study was conducted on an Acuff sandy clay loam (fine-loamy, mixed, thermic Aridic Paleustoll) located at the USDA, Agricultural Research Service Cropping Systems Research Laboratory at Lubbock, Texas. The soil surface had 24% clay, 53% silt, and 0.3% organic matter. The study was conducted on an experimental plot that had been uncultivated for several years. The entire site was intensively cultivated to break up and remove large clods and create a relatively uniform surface, free of weeds and plant residues. The final tillage was performed with a chisel tool that produced ridges approximately 92 mm high and 250 mm apart (Fig. 1(a)). The geometric mean diameter

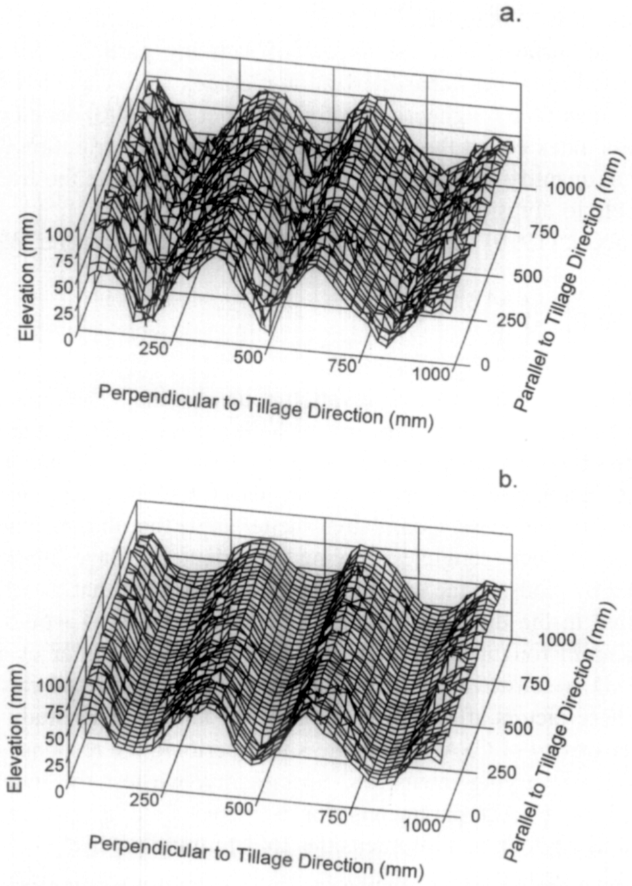


Fig. 1. Representative plot surfaces after initial plot preparation (a) and after 83 mm rainfall (b) at an intensity of 78 mm $h^{-1}$.

of aggregates after the final tillage, as measured by rotary sieve (Chepil, 1962), was 4.74 mm and the geometric standard deviation was 0.148.

The site was divided into eight plots, composed of two blocks (replications). Four rainfall intensities were randomized within each block. Rainfall was applied at intensities of 13, 25, 51, and 76 mm $h^{-1}$. The rainfall simulator (Norton and Brown, 1992) utilized Veejet 80100 nozzle [1] which produced a rainfall energy of approximately 20 J $m^{-2}$ $mm^{-1}$ of simulated rainfall (Baumhardt et al., 1990) over an area approximately 2 m wide and 3 m long. The rainfall intensities were selected to represent a wide

[1] Use of trade, firm, or corporate names is for information and convenience of the reader. Such use does not constitute an official endorsement or approval by the USDA, Agricultural Research Service of any product or service to the exclusion of others that may be suitable.

range with the maximum rainfall intensity slightly below the 100-year 60 min precipitation estimated by NOAA for the region (Frederick et al., 1977).

Roughness measurements were made with a laser roughness meter (Huang and Bradford, 1990) after 0, 6, 19, 32, 44, 57, and 83 mm of cumulative simulated rainfall at each rainfall intensity. Thus, the experimental design was a randomized complete block with rainfall amount and intensity as the factors (SAS Institute, 1990). The surface was allowed to dry for several days and become air-dry after each rainfall amount before applying additional rainfall. We felt this procedure simulated the effect of a series of small rains that often occur in this region. The effect of continuous application of rainfall up to each cumulative rainfall amount would probably produce a different effect on the soil surface. Evaluation of the effect of continuously applying rainfall was not an objective of this study.

A total of 52 plots were measured for this study because only one replication was measured for the 51 mm $h^{-1}$ rainfall intensity for 32, 44, 57, and 83 mm rainfall amounts owing to an accident that damaged the plot surface of the second replication (2 replications × 4 intensities × 7 rainfall amounts minus 4 bad replications = 52). Calculations were made using 41 750 observations on a 1 $m^2$ plot within each rainfall simulation area. Elevation observations were made approximately every 6 mm parallel to the tillage direction and every 4 mm perpendicular to tillage. Reference pins were located at the corners of each plot to realign the roughness meter after each rainfall event. The ridge height of each plot was calculated as the difference between the average of the highest 2% and the average of the lowest 2% of observations. Correlations between *FSA* and ridge height were tested for significance.

## 2.2. Wind erosion roughness index calculation

Details of the procedure to calculate the CSAD, a wind erosion roughness index, are described by Potter et al. (1990) and summarized here. The index was based on a shelter angle concept. The shelter angle was defined as the minimum angle a particle must descend in order to strike a given observation point yet not impact the soil surface (Fig. 2). The shelter angle for each elevation observation point measured on a plot was determined in a given direction considering only adjacent observation points within a specified zone of influence. For the zone of influence in this study, we tested all points

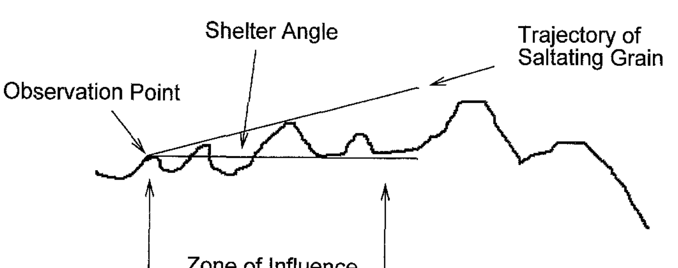


Fig. 2. Schematic cross-section of the soil surface showing the shelter angle and zone of influence used in cumulative shelter angle distribution calculations.

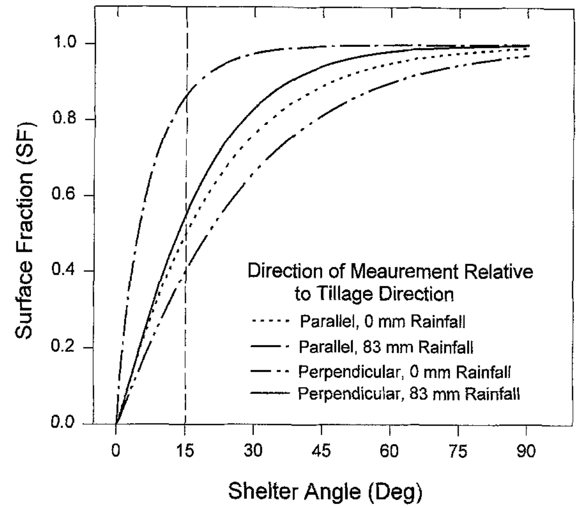


Fig. 3. Representative cumulative shelter angle distributions measured parallel and perpendicular to the tillage direction after initial plot preparation and after 83 mm rainfall at an intensity of 78 mm h$^{-1}$.

within 0.3 m from the observation point being evaluated. A zone of influence of 0.3 m was selected because Sorensen (1985) reported a mean jump length of 0.3 m for saltating sand. For observation points with a negative shelter angle, indicating that the observation point had a higher elevation than other points within 0.3 m, the shelter angle was set to zero. The CSAD is represented as the plot of cumulative fraction of observation points having a shelter angle less than a given shelter angle (surface fraction, SF) versus the given shelter angle (SA) as illustrated in Fig. 3. Each CSAD is mathematically described using a two-parameter Weibull distribution (Johnson and Kotz, 1970) as shown in Eq. (1). In this study, the CSAD $B$ and $C$ parameters in Eq. (1) were estimated using a non-linear least squares procedure provided in PROC NLIN of the SAS Institute (1990).

Shelter angles were calculated for all plot observation points in directions parallel and perpendicular to the tillage direction. We measured CSAD in directions parallel and perpendicular to tillage because these directions represent the extreme values of roughness measured on a field with oriented tillage marks.

Since the CSAD allows us to quantify the fraction of measured points with shelter angles equal to or less than a specified angle, it provides an estimate of the fraction of the surface susceptible to abrasion by particles descending at angles equal to or less than the descent angle of saltating particles. During wind erosion, saltating soil particles usually strike the soil surface at an angle of approximately 12–15° (Sorensen, 1985). The CSAD concept can be used to estimate the *FSA* by setting SA in Eq. (1) to 15° to represent the descent angle of saltating particles.

Since both $B$ and $C$ parameters were used in the CSAD to estimate the surface fraction susceptible to abrasion, multi-variate analysis of variance (MANOVA) was used to evaluate the effects of rainfall amount, intensity, and the interaction of rainfall amount and intensity on $B$ and $C$ simultaneously. Univariate analyses of variance (ANOVA)

Table 1
Cumulative shelter angle distribution parameters derived from a test plot before rainfall and after 83 mm rainfall applied at an intensity of 76 mm $h^{-1}$

| Rainfall amount (mm) | Direction relative to tillage | | | | | |
|---|---|---|---|---|---|---|
| | Parallel | | | Perpendicular | | |
| | *B* | *C* | *FSA* | *B* | *C* | *FSA* |
| 0 | 21.20 | 1.06 | 0.50 | 27.73 | 1.08 | 0.40 |
| 83 | 6.88 | 0.89 | 0.86 | 18.18 | 1.16 | 0.55 |

*B*, *C*, *FSA*: cumulative shelter angle distribution *B* and *C* parameters and surface fraction susceptible to abrasion, respectively. Fraction susceptible to abrasion was the proportion of points with shelter angles of 15°or less.

were performed on the *B* and *C* parameters separately and on *FSA* and ridge height to determine which (or if) parameters were affected by rainfall amounts, intensity, and the interaction of rainfall amount and intensity. When significant interactions of rainfall amount and intensity were found, the parameter values were regressed against rainfall amount for each rainfall intensity. Covariance analyses were done to evaluate differences in slopes or intercepts of these regressions. Statistical significance tests were at $P < 0.05$.

## 3. Results

A three-dimensional graph of a representative plot immediately after initial plot preparation is shown in Fig. 1(a) and the same plot after 83 mm simulated rainfall at a 76 mm $h^{-1}$ intensity is shown in Fig. 1(b). Effects of rainfall amount and direction of measurement relative to tillage on CSAD parameters for this plot are summarized in Table 1 and illustrated in Fig. 3. The CSAD for the plot after 83 mm rainfall is shifted up and to the left relative to the plot before rainfall was applied. In addition, the CSAD measured parallel to the tillage direction was shifted up and to the left relative to the corresponding perpendicular CSAD. Summary statistics for the CSAD *B* and *C* parameters and *FSA* for the entire experiment are listed in Table 2.

The MANOVA, used to test the *B* and *C* parameters simultaneously, showed a

Table 2
Summary statistics of roughness indexes measured [a]

| Roughness index | Mean | Maximum | Minimum | CV (%) |
|---|---|---|---|---|
| CSAD [b] parallel *B* value | 19.48 | 28.15 | 6.88 | 25.28 |
| CSAD parallel *C* value | 1.06 | 1.18 | 0.82 | 7.42 |
| CSAD perpendicular *B* value | 29.75 | 37.71 | 18.18 | 16.03 |
| CSAD perpendicular *C* value | 1.29 | 1.51 | 1.03 | 10.99 |
| Parallel *FSA* [c] | 0.54 | 0.86 | 0.38 | 20.60 |
| Perpendicular *FSA* | 0.35 | 0.55 | 0.22 | 23.74 |

[a] total of 52 observations.
[b] CSAD is cumulative shelter angle distribution.
[c] *FSA* is fraction susceptible to abrasion, estimated as the proportion of points with shelter angles of 15° or less.

Table 3
Probability of obtaining a greater $F$ from univariate analyses of variance of roughness indexes, by rainfall amount and intensity

| Source | Direction relative to tillage | | | | | |
|---|---|---|---|---|---|---|
| | Parallel | | | Perpendicular | | |
| | *B* | *C* | *FSA* | *B* | *C* | *FSA* |
| Amount ($A$) | 0.0001 | 0.0001 | 0.0001 | 0.0074 | 0.98 | 0.10 |
| Intensity ($I$) | 0.0001 | 0.0001 | 0.0001 | 0.0042 | 0.33 | 0.0195 |
| $A \times I$ | 0.0001 | 0.0001 | 0.0001 | 0.83 | 1.00 | 0.98 |

*B*, *C*, *FSA*: cumulative shelter angle distribution *B* and *C* parameters and surface fraction susceptible to abrasion, respectively. Fraction susceptible to abrasion was the proportion of points with shelter angles of 15° or less.

significant interaction ($P < 0.05$) of rainfall amount and intensity for the *B* and *C* parameters for observations parallel and perpendicular to tillage. The univariate ANOVA showed rainfall amount, intensity and their interaction had significant effects on *B*, *C*,

Table 4
Linear regression statistics for each CSAD parameter, by direction relative to tillage and rainfall intensity

| Eq. no. | Parameter | Rainfall intensity ($mm\,h^{-1}$) | Intercept | Slope | Prob of $> F$ | $R^2$ |
|---|---|---|---|---|---|---|
| *Parallel* | | | | | | |
| 1 | *B* | 13 | 22.8 | −0.01 | 0.07 | 0.25 |
| 2 | *B* | 25 | 24.0 | −0.11 | 0.0001 | 0.95 |
| 3 | *B* | 51+76 | 23.7 | −0.20 | 0.0001 | 0.84 |
| 4 | *C* | 13 | 1.12 | −0.0003 | 0.02 | 0.39 |
| 5 | *C* | 25 | 1.12 | −0.001 | 0.0001 | 0.84 |
| 6 | *C* | 51 | 1.11 | −0.002 | 0.0015 | 0.74 |
| 7 | *C* | 76 | 1.11 | −0.004 | 0.0001 | 0.85 |
| 8 | *FSA* | 13 | 0.465 | 0.0003 | 0.06 | 0.27 |
| 9 | *FSA* | 25 | 0.443 | 0.002 | 0.0001 | 0.95 |
| 10 | *FSA* | 51 | 0.453 | 0.004 | 0.0001 | 0.92 |
| 11 | *FSA* | 76 | 0.443 | 0.005 | 0.0001 | 0.89 |
| *Perpendicular* | | | | | | |
| 12 | *B* | 13 | 32.8 | −0.003 | 0.89 | 0.00 |
| 13 | *B* | 25 | 32.6 | −0.07 | 0.024 | 0.36 |
| 14 | *B* | 51+76 | 32.9 | −0.16 | 0.0001 | 0.63 |
| 15 | *C* | 13 | 1.35 | 0.0004 | 0.75 | 0.01 |
| 16 | *C* | 25 | 1.28 | −0.0007 | 0.56 | 0.03 |
| 17 | *C* | 51 | 1.32 | −0.002 | 0.15 | 0.24 |
| 18 | *C* | 76 | 1.28 | −0.0004 | 0.82 | 0.00 |
| 19 | *FSA* | 13 | 0.296 | −0.0001 | 0.91 | 0.00 |
| 20 | *FSA* | 25 | 0.309 | 0.001 | 0.11 | 0.20 |
| 21 | *FSA* | 51+76 | 0.302 | 0.002 | 0.0001 | 0.5 |

*B*, *C*, *FSA*: cumulative shelter angle distribution (CSAD) *B* and *C* parameters and surface fraction susceptible to abrasion, respectively. Fraction susceptible to abrasion was the proportion of points with shelter angles of 15°or less.

and *FSA* with observations parallel to tillage (Table 3). Perpendicular to tillage, only *B* was affected by the main effect, rainfall amount, while the *B* and *FSA* were affected by rainfall intensity. Interactions of rainfall amount and intensity with observations in the direction perpendicular to tillage were not significant for *B*, *C*, or *FSA* (Table 3). There were no significant effects on ridge height owing to rainfall amount, intensity or their interaction.

Since significant effects were observed for *B*, *C*, and *FSA*, simple linear regressions of these response variables over rainfall amount by rainfall intensity were done in an attempt to better understand the effects of rainfall intensity and rainfall amount (Table 4). Although there were no significant effects for *C* values measured perpendicular to tillage, the regressions were done to determine why the results were different for this parameter.

The correlation between *FSA* measured in the direction parallel to tillage and ridge height was $-0.48$ while the correlation between *FSA* measured in the direction perpendicular to tillage and ridge height was $-0.60$. Both correlations were significantly different from zero.

## 4. Discussion

### 4.1. Effect of measurement direction on CSAD parameters

Comparisons of *FSA* (made by setting the shelter angle to 15°) allow us to quantify changes in the CSAD using a very practical parameter because it is a point on the CSAD curve that directly relates to soil abrasion and wind erosion (Fig. 3). The net effect of the shift up and to the left was to increase the surface fraction susceptible to abrasion by saltating particles. The changes in *FSA* after 83 mm of simulated rainfall, as described in Table 1 and illustrated in Fig. 3, demonstrate this effect.

Rainfall increased *FSA* in both directions measured relative to tillage and the amount of increase after rainfall depended on the direction measured (Table 1). After 83 mm of rainfall, the *FSA* increased 15% when measured in the direction perpendicular to tillage (0.40 versus 0.55) and 36% when measured in the direction parallel to tillage (0.50 versus 0.86). In addition, the *FSA* measured in the direction parallel to tillage was greater than that measured in the direction perpendicular to the tillage when comparing the effect of measurement direction at the same rainfall amount. The estimated *FSA* after initial plot preparation (0 mm rainfall) was 10% greater in the direction parallel to tillage than perpendicular to tillage and the estimated *FSA* was 31% greater in the direction parallel to tillage than perpendicular to tillage after 83 mm rainfall. However, after 83 mm rainfall there was 0.55 *FSA* in the direction perpendicular to tillage suggesting that ridge height alone was inadequate to protect the surface in this situation. The protection of the soil surface provided by random roughness as suggested by *FSA* measured parallel to tillage was lower and decayed more rapidly than the protection produced by the combination of random and ridge roughness estimated by *FSA* measured perpendicular to tillage.

The difference in protection measured relative to tillage direction was observed throughout the experiment. In a comparison of the means averaged over the entire experiment, the CSAD *B* and *C* parameters were greater and *FSA* was lower (Table 2) when measured perpendicular to the tillage direction than when measured in the parallel direction causing shifts in the CSAD parameters similar to those shown in Table 1. The mean estimated *FSA* of all plots was 19% greater in the direction parallel to tillage than perpendicular to tillage. This difference in estimated *FSA* between directions parallel and perpendicular to tillage shows that low oriented tillage marks provided significant additional protection of the soil surface from the impact of saltating grains.

Simple linear regressions of *B*, *C*, and *FSA* over rainfall amount, by rainfall intensity, measured parallel to the tillage direction are shown in Table 4. The regression lines describe how each CSAD parameter responded to rainfall. Although each regression line is described by the intercept and slope, we will focus our discussion on the slopes of the regression lines because the initial conditions of the plots (as represented by the intercept of the lines) were very similar. The slopes describe the rate of change in the roughness parameter in relation to rainfall amount. Differences in slopes were clearly related to direction of observation. Observations measured parallel to tillage almost always had greater slopes than those evaluated perpendicular to tillage at the same rainfall intensity. For example, slopes of regressions of *FSA* over rainfall amount parallel to tillage were two or more times greater than those of regressions perpendicular to tillage at the same rainfall intensity. Thus, increasing rainfall amounts at any rainfall intensity increased exposure of the soil surface to erosion more rapidly when evaluated parallel to the direction of tillage marks than when evaluated perpendicular to tillage.

### *4.2. Observations parallel to tillage*

For calculations made parallel to the direction of tillage, the CSAD parameters appeared very sensitive. This is supported by the ANOVA which showed that rainfall amount, intensity, and their interaction had significant effects on all parameters. The simple linear regression of *B*, *C* and *FSA* over rainfall amount, by rainfall intensity, described the relationships in more detail.

Covariance analysis, used to test for differences among regressions, indicated that regressions for *B* evaluated parallel to tillage were not all different (Table 4). The regression for the lowest rainfall intensity, $13\,\mathrm{mm\,h^{-1}}$, was significantly different from $25\,\mathrm{mm\,h^{-1}}$. The regressions for the higher intensities (51 and $76\,\mathrm{mm\,h^{-1}}$) were not significantly different from one another, meaning that the data for these intensities could be fitted with one regression (Eq. 3, Table 4). This was due, in part, to lack of replications of $51\,\mathrm{mm\,h^{-1}}$ data and greater variability of observations for $76\,\mathrm{mm\,h^{-1}}$ data. Fig. 4(a) shows that, for rainfall amounts less than about 45 mm, the range of *B* values for the 51 and $76\,\mathrm{mm\,h^{-1}}$ lines overlap. For the *C* parameter and *FSA* evaluated parallel to tillage (Fig. 4(b) and Fig. 4(c), respectively), covariance analysis showed that a different regression is required for each rainfall intensity.

Having established which regressions were different from the others, it is constructive to consider the general trends of the lines. Fig. 4 and Table 4 show that the $13\,\mathrm{mm\,h^{-1}}$ rainfall intensity did not cause much change in the soil surface microrelief even after

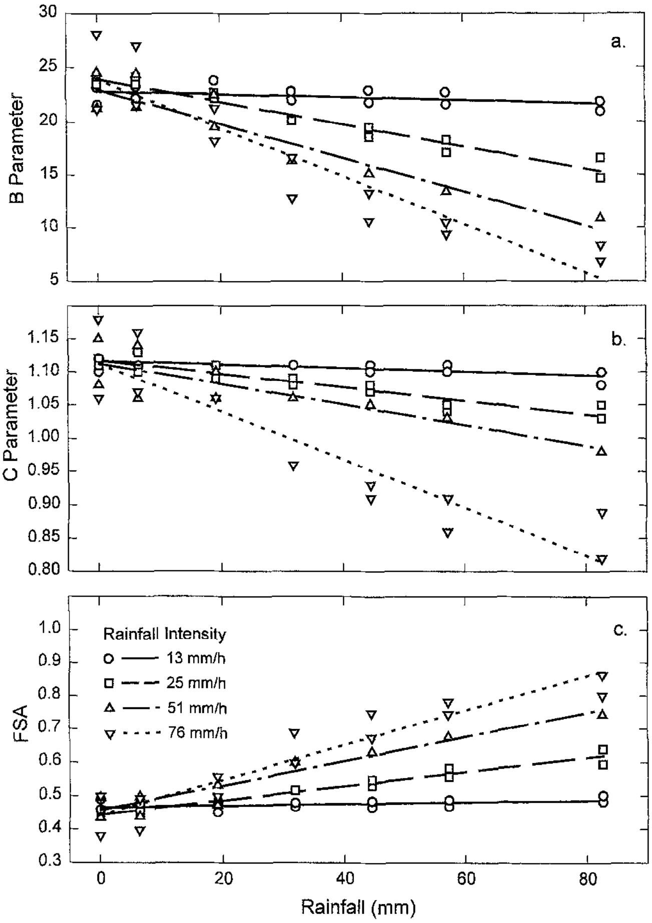


Fig. 4. Effect of rainfall on cumulative shelter angle distributions (a) *B* parameters and (b) *C* parameters; and (c) fraction susceptible to abrasion (*FSA*) for four rainfall intensities measured parallel to the tillage direction.

83 mm rainfall for observations parallel to tillage. The slopes of all regression lines for all parameters are very flat in the figures, and the regressions for most parameters tested were not significant at the 0.05 level. For regressions evaluated at 25 mm $h^{-1}$ rainfall intensity and the combined 51 and 76 mm $h^{-1}$ intensity, the *B* and *C* parameters and *FSA* data were all significant and account for over 70% of the variation of the data (Table 4).

### 4.3. Observations perpendicular to tillage

For observations made perpendicular to the direction of tillage, the CSAD parameters were far less sensitive to the effects of rainfall. Only the *B* parameter was significantly affected by rainfall amount, while both *B* and *FSA* were significantly affected by rainfall intensity (Table 3). Since the *B* parameter was affected by rainfall amount and

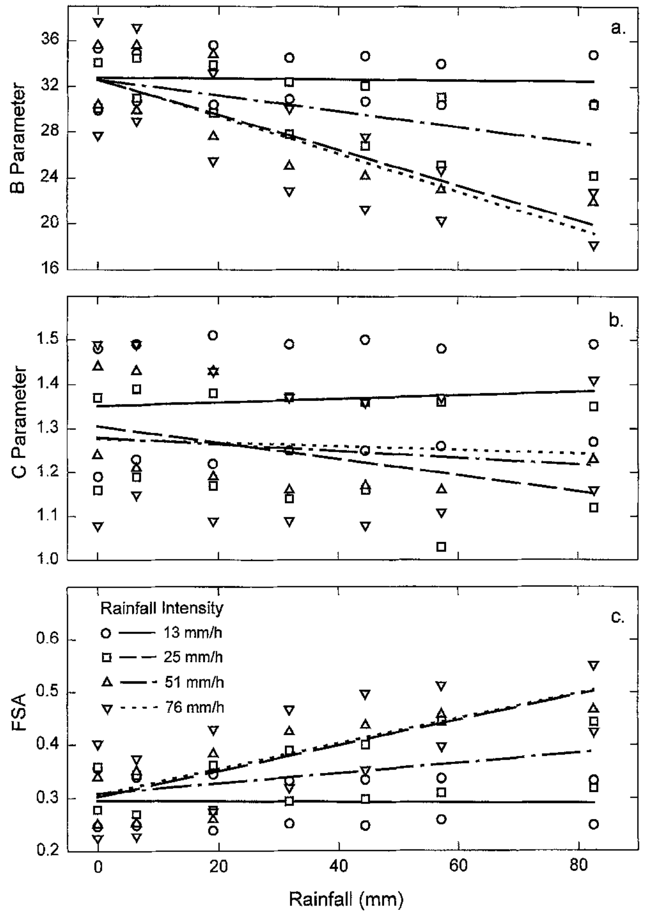


Fig. 5. Effect of rainfall on cumulative shelter angle distributions (a) $B$ parameters and (b) $C$ parameters; and (c) fraction susceptible to abrasion ($FSA$) for four rainfall intensities measured perpendicular to the tillage direction.

the $B$ parameter is one of the parameters that describes the distribution, it is possible that some other point on the CSAD other than $FSA$ was affected by rainfall. We did not test this possibility in this study.

For evaluation perpendicular to tillage, ANOVA also showed no significant effects for the $C$ parameter (Table 3). It would be sufficient to use the average value of the $C$ parameter over all rainfall amounts and intensities, 1.29. In addition, regressions for the $C$ parameter were flat (Fig. 5(b)), slopes near zero with low $R^2$ values, and covariance analysis showed no significant differences between regressions (Eqs. 15–18, Table 4). For $B$ evaluated perpendicular to tillage, regressions were not all significantly different (Fig. 5(a)). Again, three regressions could be used for the relationship of $B$ parameter to rainfall amount. The regressions for 51 and 76 mm h$^{-1}$ intensities were not significantly different so the data were combined to fit one regression equation (Eq. 14, Table 4).

Although significant, the regressions of the $B$ parameter for the 25 mm h$^{-1}$ rainfall intensity and the combined 51 mm h$^{-1}$ and 76 mm h$^{-1}$ intensity data (Eqs. 13 and 14, Table 4) accounted for far less of the variability than comparable $B$ parameter equations evaluated parallel to tillage (Eqs. 2 and 3, Table 4). Similarly, covariance analysis suggested three regressions could be used for relating *FSA* to rainfall amount (Fig. 5(c)). The data for 51 and 76 mm h$^{-1}$ were combined to fit the regression (Eq. 21, Table 4) because the separate regressions were not significantly different. However, only the regression for the combined 51 and 76 mm h$^{-1}$ data was significant for *FSA* evaluated perpendicular to tillage (Table 4).

### 4.4. Ridge height versus fraction susceptible to abrasion

The correlation test showed a significant negative correlation of ridge height and *FSA*. The significant correlation of ridge height and *FSA* measured perpendicular to the tillage direction was expected since we measured across tillage ridges. It seems reasonable to expect that, as the height of the ridges decayed, the fraction of the soil surface sheltered by these lower ridges also decayed, causing a greater fraction to be susceptible to abrasion.

The reason for the negative correlation of ridge height and *FSA* measured parallel to the tillage direction is not as straightforward. When we measured shelter angles in the direction parallel to the tillage direction we did not cross ridges and so assumed any ridge effects would not be detected. We speculate the correlation of ridge height and *FSA* measured parallel to the tillage direction might be attributed to a combination of the following factors. (1) The tillage ridges were not perfectly straight causing some ridge height effect to be included on crooked ridges. (2) Rainfall caused the elevations of both clods and ridges to decay and the imperfect correlation was due to the different, and not highly correlated, rates of decay of clods and ridges. (3) The roughness meter might not have been perfectly aligned and measurements were made along a slight angle, not exactly parallel, to the tillage ridges.

## 5. Conclusions

We feel this study demonstrated the use and sensitivity of CSAD for estimating the fraction of the soil surface susceptible to abrasion by saltating particles. We used the CSAD to estimate how *FSA* changed for calculations made relative to tillage direction, and with varying rainfall amounts and intensities. The relatively smooth but slightly ridged field produced significant differences in CSAD parameters.

Our study showed that although ridge height and *FSA* were correlated, CSAD parameters were more discriminating than ridge height in describing changes in surface roughness owing to rainfall amount, intensity and their interaction. We found many significant differences in CSAD parameters, but we found no significant differences in ridge height owing to any controlled variable.

The effect of rainfall on CSAD parameters was significantly influenced by rainfall intensity when observations were either parallel or perpendicular to tillage marks. The fraction of the soil surface that would be susceptible to the impact of saltating grains that produce wind erosion increased with cumulative rainfall and the rate of increase was generally proportional to the rainfall intensity. Regressions of *B*, *C*, and *FSA* over rainfall amount for each rainfall intensity showed that, in general, the data for the 51 and 76 mm $h^{-1}$ rainfall intensities could be combined. Regressions of *B*, *C*, or *FSA* over rainfall amount for all other rainfall intensities were different from one another.

Increasing the rainfall intensity increased the rate of change of the soil surface regardless of direction evaluated. Each rainfall intensity observed in this study produced a different effect on the parameters tested. The lowest rainfall intensity of 13 mm $h^{-1}$ produced no significant change in the soil surface. For the other intensities, the rate of change in CSAD parameters increased with increasing rainfall intensity with the exception of the *C* parameter evaluated perpendicular to tillage. There were no differences in the *C* parameters among rainfall intensities over all rainfall amounts in the direction perpendicular to tillage.

This study emphasizes the reason tillage can be an important wind erosion control practice. We found the CSAD parameters were sensitive to tillage direction for fields with tillage ridges that were only about 92 mm high. The mean *FSA* was 19% greater, and the rate of change of *FSA* over rainfall amount was twice that when evaluated parallel to tillage compared with measurements made perpendicular to tillage. The protection of the soil surface provided by random roughness as suggested by *FSA* measured parallel to tillage is lower and decays more rapidly than the protection produced by the combination of random and ridge roughness estimated by *FSA* measured perpendicular to tillage. By tilling the soil perpendicular to the dominant erosive wind, less of the soil surface will be exposed to the impact of abrading particles. Additionally, the increase in surface fraction susceptible to abrasion after rainfall will not be as great in the direction perpendicular to tillage compared with in the direction parallel to tillage.

Future work is needed to test other surfaces and soils. Since this study investigated a relatively smooth tilled surface and showed significant differences among rainfall intensities, the effect of rainfall intensity on roughness parameters for rougher tilled surfaces and for different soils needs to be evaluated.

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